PROTECTION AGAINST BLAST EFFECTS IN UXO CLEARANCE OPERATIONS

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ABSTRACT

This paper presents the results of a full-scale test series (1998), where instrumented mannequins exposed to a range of blast loading conditions were used to assess: a) some forms of injury potential posed to unprotected UXO/EOD technicians, and b) the level of protection that can be expected with the latest generation of Canadian personal protective ensembles for bomb disposal. A range of high explosive charges of C4 were used (0.5 to 17.5kg; 1.1 to 38.5 lb), at different stand-off distances from the mannequins (0.85 to 5 m; 2.8 to 16.4 ft). An analysis of the overpressures and accelerations experienced by the head (or ear) and chest of the mannequin exposed to blast is used as the basis for providing quantitative estimates of related injuries that can be sustained.

I. INTRODUCTION

Personal protective ensembles can greatly diminish the risk of serious or life-threatening injury to personnel involved in UXO clearance operations. The design should provide *properly balanced protection* against all *four conventional Life Critical Threats* associated with an explosive blast event (Photo 1 illustrates vividly the violence associated with such an explosion for a charge of 5.1 kg/11.2 lb C4):

1. **Overpressure:** The blast wave, in the form of a transmitted pressure wave, can generate various levels of compressive and shear stresses which can lead to critical injury of the thorax, serious injury to the abdominal region and permanent disabilities to the ears.
2. **Fragmentation:** Fragment penetration can range from mild abrasions of the skin to fatal injuries of the brain, brain stem, heart and great vessels, and liver.
3. **Impact (Blast Induced Body Accelerations/Decelerations):** The blast wave can cause life-threatening injuries arising from blast induced accelerations between different body parts. The body can generally be uncontrollably propelled from its original position. This will lead to a secondary impact (or deceleration), usually with a solid surface such as the ground. Associated injuries that may be incurred during both the acceleration and the deceleration phase can range from minor sprains to amputations and/or massive brain damage.
4. **Heat (Flash and Contact Burning):** In an explosive incident heat and / or flame (flash) is produced which may lead to severe burn injuries. Both direct contact with the flame and intense radiant heat can be the sources of injury.

Extensive testing has been conducted in Canada over the last 18 years to evaluate the protection capability of various suits and helmets used in Explosive Ordnance and UXO Disposal and Mine Clearance. Blast tests (both small- and full-scale) constitute a crucial element in the design and performance verification process.

This contribution summarizes the results of a full-scale test series conducted under the auspices of the Royal Canadian Mounted Police (RCMP) at the Defence Research Establishment Valcartier (DREV). Prior to these trials, two other full-scale test series had been conducted in 1994 and 1996, as well as numerous rounds of small-scale testing, which were performed between 1996 and 1998 at the Blast Chamber Facilities of Energy Mines and Resources (EMR), Canada, the head impact 'Drop Tower' at Biokinetics and Associates, Ottawa, and the Shock Wave Physics Laboratory of the Department of Mechanical Engineering, McGill University, Montreal.

Extensive fragmentation testing of the different ensemble components was performed in parallel throughout the whole program. The fragmentation resistance was determined using the 17 grain fragment simulator according to the STANAG 2920 Test Specification.

A comprehensive test report [1] summarizes the findings for the latest generation of protective ensembles (EOD-8). The overall intent of the current study is to evaluate and quantify the performance of these protective ensembles against blast overpressure (chest and ear) and impact (blast induced chest and head accelerations).

II. EXPERIMENTAL DETAILS

II.1 Test Devices and Instrumentation

Overpressure tests were conducted with two different kinds of test devices, namely chest simulators and instrumented anthropomorphic test mannequins. The former were used in both small-scale and large-scale tests, while the latter were primarily utilized in the full-scale trials at DREV.

The chest simulator used in these experiments is essentially comprised of a curved aluminum plate (12.7 mm (½") thick) bolted down on a flat aluminum base plate, in order to allow for protective laminations to be mounted on a contour roughly similar to the human torso and be tested. These protective laminations represent the parts of the protective ensemble that would cover the chest region of a wearer. Up to eight piezoelectric pressure transducers can be placed at various locations on the chest simulator with their face flush mounted on the exposed surface. This arrangement permits the face-on (i.e. normally reflected) pressure from the explosion to be measured at selected positions of the frontal chest area. In a typical experiment, the test sample is placed over the central part of the simulator. Following an explosion, the pressure sensors located underneath this sample monitor the overpressure transmitted through the protective lamination to the chest wall. Another sensor is usually left uncovered in order to measure the reference face-on overpressure at the chest surface without any protection. Photo 2a shows one of the two simultaneously used chest simulators in a typical large-scale test setup, mounted vertically and rigidly supported on concrete blocks so that its face was exposed to the blast.

For the purpose of full-scale testing, two pedestrian model anthropomorphic test devices, i.e., automotive crash test mannequins (HYBRID II), which are representative of a 50th percentile male subject (height=1.75m, mass=77kg), were fully dressed in protective equipment and subjected to blasts from high explosives. In this test series the mannequins were placed on a specially designed base plate and supported in the standing position by means of an anchored small diameter steel pipe slipped underneath each armpit (see Photo 2a).

Both HYBRID II mannequins were equipped with two clusters of tri-axial accelerometers (one located in the head, one in the chest), along with three pressure transducers for measuring the face-on overpressure on the upper and lower parts of the sternum and the side-on overpressure in the ear. Photo 2b shows the mannequin during the instrumentation process, while the instrumented mannequin, wearing a complete protective ensemble and supported in the standing position, is depicted in Photo 2a.

In addition to monitoring the blast overpressure with the help of the sensors placed in the chest simulators and the mannequins, free-field (side-on) overpressure was measured by means of four lollipop type transducers. These lollipop transducers were usually positioned at radii of 3 and 5 m (9.84 and 16.4 ft) from the center of the explosive charge. In total, 32 sensors were used in each trial for pressure and acceleration measurements.

Each test was photographically recorded by means of a continuously running video camera and also by two high-speed digital cameras, set to a speed of 1000 frames/second. In each experiment, the high-speed cameras were triggered with appropriate delay generators at the time of charge detonation. They were located in two shelters left and right of the test area at a distance of about 70 m (229.7 ft) from the explosive charge. This separation distance between the cameras and the explosion center was necessary to minimize camera movement induced by the shock wave.

II.2 Explosive Charge Size and Setup Layout

Charge size and setup layout were chosen to yield blast loadings representative of realistic threats. For overpressure and impact, measurements were taken for distances ranging from 0.85 to 5 m (2.8 to 16.4 ft). It was found that the most meaningful data could be obtained for a test specimen at a stand-off distance from the charge of 3 m (9.84 ft). The charge size was selected from a range in mass of 5.1 to 17.5 kg (11.2 to 38.5 lb), in order to generate a blast profile at this distance that would correspond as much as possible to the blast loading likely to be encountered in a real-life scenario. Smaller charges, down to 0.5 kg (1.1 lb), were chosen for tests with lower stand-off distances.

For the majority of the tests, in which the mannequins and chest simulators faced a blast wave at a distance of 3 m (9.84 ft), the explosive charge consisted of high explosive (C4) contained within a weak cardboard cylinder, of diameter equal to its length (i.e., aspect ratio of unity), to resemble a spherical charge. The explosives-packed cylinder was placed on a tube made from thin cardboard so that the centre of the charge was located at 1 m (3.28 ft) off the ground and nominally 3 m (9.84 ft) away from the different test specimens, as shown in Photos 1 and 2a. A blasting cap submerged to the center of the cylindrical charge was used to initiate detonation.

III. BLAST OVERPRESSURE PROTECTION

III.1 Measurements of Overpressure

It should be noted that all pressure transducers mounted in the chest simulators and the mannequins – with the exception of the transducer that records ear pressure – were positioned to monitor a *face-on overpressure*. This pressure corresponds to the total loading that an object hit face-on by a blast wave would experience. In simple terms, it is comprised of two parts: the static *side-on overpressure* behind the blast wave, which would be established regardless of the presence of an object, and the additional ‘dynamic’ portion caused by the fact that the gases, set in motion by the blast wave, are decelerated and brought to rest by an object, which stands in the path of a blast wave. The latter part not only depends on the blast wave (i.e. its strength to move the initially quiescent gas) but is also a function of the object itself, its geometry, its properties and consistency, which determine to what extent these gases are brought to rest and how much of the blast wave is reflected. To simplify matters, all injury assessment has been based entirely on the aforementioned *side-on overpressure*, which is characteristic of just the blast wave strength and independent of the object. In the case of a rigid, non-moving object, both pressure values are related and the corresponding side-on overpressure may be determined from a face-on overpressure measurement.

The experimentally determined side-on overpressure range for the specified charges corresponded with sufficient accuracy to the respective side-on overpressure values that can be established for a *hemispherical* blast wave: 4.7 to 11.9 bar (70 to 173 psi) at a distance of 3 m (9.84 ft). These values of peak side-on overpressure were chosen as nominal reference (see Table 1).

charge size [kg / lb] C4	**distance [m / ft]**	**side-on overpressure [bar / psi]**	**face-on overpressure [bar / psi]**
5.1 / 11.2	3 / 9.84	4.7 / 68.3	20.59 / 298.6
10 / 22	3 / 9.84	7.9 / 114.1	40.35 / 585.1
17.5 / 38.5	3 / 9.84	11.9 / 172.3	68.72 / 996.4

Table 1: Nominal test conditions for large-scale trials

III.2 Overpressure Reductions

An analysis of the pressure traces indicates that the configuration in the full-scale trials creates ground-reflected waves, which augment/amplify the overall profile and in particular the duration of the incident blast wave, compared to the wave profiles observed in the blast chamber tests, where the charge was suspended in a way that only the incident blast wave reached the chest simulator (without any interaction with walls or other boundaries) [1]. Consequently, a more adverse loading scenario is observed in the full-scale tests, which is reflected in a slightly worse performance of the protective ensemble. Figures 1a and 1b show typical overpressure reductions behind the EOD-8 frontal chest lamination for blast conditions of 4.7 and 7.9 bar (68 and 115 psi) side-on overpressure, respectively, which corresponds to 5.1 kg C4 and 10 kg C4 (11.2 and 22 lb), respectively, at a distance of 3 m (9.84 ft). The pressure is measured simultaneously on a chest simulator and on an instrumented mannequin. The transducers used for the presented traces are located at approximately the same height off the ground. In each figure, all traces are recorded in the same experiment; the unprotected transducer for the reference trace is located on one of the chest simulators.

The face-on overpressure measured on the upper and lower sternum of the bare HYBRID II mannequin (without any protective suit) is in agreement with values measured by an unprotected transducer on the chest simulator, if both devices are placed at the same distance from the explosive center. Once the mannequins were fully dressed in the protective ensemble, however, the face-on overpressures measured at the mannequin sternum were consistently lower (typically by up to 60%) than values measured at the chest simulator with the same bomb suit lamination mounted over the pressure sensors, as can be seen in the corresponding traces of Figs. 1a and 1b. This is likely attributed to the fact that in mannequin measurements there exists a fixed air gap between the chest protection lamination and the pressure sensors, which were mounted on the recessed sternum. On the chest simulator, the samples make complete contact with the surface. If an air gap between the pressure sensor mounted on the sternum and the actual chest lamination can be preserved throughout the blast loading phase, the sensor is likely to measure only the transmitted gas pressure. In this case, the motion of the lamination of protective materials, induced by the passage of the shock wave, does not physically load the chest through direct contact.

Another reason for the difference in the pressure readings may be seen in the fact that the mannequins are allowed to move under the impact of the blast wave, whereas the chest simulators are mounted on a rigid support. In trials of previous test series however [2], where the test samples were mounted on a free-floating plate, this effect was shown to contribute only negligibly to the decrease of the pressure signals in the time frame of the event.

From numerous experimental records of the form shown in Figs. 1a and 1b, derived from the blast chamber tests and the chest simulator and mannequin chest readings in the full-scale trials, the overall protective performance of the tested ensemble with respect to overpressure mitigation can be determined. The results indicate that in the frontal chest region, the peak overpressure imparted by an incident blast wave is reduced by nominally 85 % (within a range of 65% to 90%).

The closed face protective helmets (EOD-7B and EOD-8) mounted on the HYBRID II head were found to reduce overpressure in the ear region by 92-94 %, for cases where the overpressure within an unprotected ear cavity amounts to about 3.5 bar (51 psi) (see Fig. 1c). The helmet, which has energy absorbing foam at the visor/helmet interface, reduces the overpressure to the ear equally well for higher charges – however, because of the high degree of potential destruction of the instrumentation and the mannequins themselves at the loading levels associated with charges of more than 5.1 kg (11.2 lb), no reference trials with an unprotected mannequin could be conducted. Thus, no measured reduction factors can be determined.

III.3 Injury Thresholds Based on Overpressure Reductions

Based on theoretical models and experimental data available in the medical literature for biological subjects exposed to blast, one can derive curves for the free-field side-on overpressure as a function of equivalent charge mass of TNT and for different stand-off distances from the charge center, as it is presented in Fig. 2a. The injury thresholds for an unprotected human [3], based on the reference free-field side-on overpressure, are also presented in this figure in the form of horizontal lines. Thresholds and 50%

probability for injury to the ear and lung are indicated, as well as a range of probabilities for overall survival.

Important: **All injury levels indicated here have been established under the assumption that overpressure is the single source for injuries. For the assessment of injuries in a real-life scenario, other threats like fragmentation, impact and heat have also to be considered.**

For any charge mass (horizontal axis) the probability and severity of injury increases as the stand-off distance from the charge is reduced. It is important to realize that this dependency is highly non-linear and that in closer vicinity to the charge a small reduction in stand-off distance may lead to a major increase in injury probability. For an unprotected individual facing a 4 kg (8.8 lb) charge of TNT equivalent at a distance of 5 m (16.4 ft), there would exist better than 99% probability of survival and less than 50% chance of ear drum perforation **from a blast overpressure threat alone**. If some degree of ear drum perforation were to be incurred, it would constitute a minor injury for which treatment is available. Reducing the stand-off distance for the same charge to, say, 2 m (6.56 ft), would result in an individual suffering lung and ear injuries due to overpressure. While in this case the probability of some form of lung injury is high (50 %), the probability of survival is still better than 99 %. A further decrease of the stand-off by only a small increment, say, from 2 m to 1.5 m, would however reduce this probability of survival considerably, i.e., from 99% to about 40% !

The overpressure test findings described earlier indicate that the wearer of a protective ensemble would experience much lower pressure loadings (and presumably a much lower injury risk) than an unprotected person: The helmet mitigates overpressure to the ear by 92%-94% and the jacket reduces overpressure to the chest and lung regions by 65%-90%. Equivalently, for the <u>same level of injury</u> as incurred by an unprotected individual, a wearer of such an ensemble could withstand much higher overpressures outside the protective ensemble. By taking these overpressure reduction levels into account and by incorporating an appropriate safety factor [1], the thresholds for injury and probability of survival presented in Fig. 2a may be recomputed, as shown in the left part of Fig. 2b. It is readily apparent that the type and severity of injury at a given overpressure, charge mass and stand-off distance, are drastically reduced by wearing an adequate protective ensemble.

It has to be emphasized that the recomputed values represent best *estimates* of the injury levels related to a blast overpressure threat alone. The corresponding diagrams are only to be used to indicate trends and should not be interpreted as a source of absolute data for injury assessment.

For the above mentioned case (stand-off distance of 1.5 m (4.92 ft) to a 4 kg (8.8 lb) charge of TNT), where an *unprotected* individual would most likely have only a 40 % chance of survival and would most certainly suffer some form of severe lung and ear damage due to the blast overpressure, the probability of survival for a person protected with the latest generation Canadian ensemble (i.e., EOD-8) is better than 99 % !

The test results clearly highlight the advantages, from a safety standpoint, in wearing a protective ensemble such as the EOD-8 or equivalent when confronting an explosive charge. However, **in the overall assessment of injury resulting from the explosive blast, it is essential that one considers all the other sources of blast induced injury as well, i.e., fragmentation, impact, and heat**.

IV. PROTECTION AGAINST BLAST IMPACT

A class of injuries which often are not readily diagnosed and have historically not been well understood, are acceleration and deceleration type impact injuries. In the context of an explosive blast, the initial collision and subsequent interaction of a shock wave with a victim can induce violent uncontrolled motion between body parts. The relative accelerations of the different components are a function of their mass, size, and shape compared to the blast wave parameters. Dependent on the blast severity, the body as a whole may accelerate and be launched for tens of metres from its origin. Resulting injuries can range from minor sprains to generally unsurvivable situations associated with concussion. Deceleration type injuries can occur when a victim impacts directly against a rigid surface/obstacle following displacement, or launch, by the force of the blast. Injuries range from minor sprains, lacerations, bruises and fractured bones to ruptured organs, spinal injuries and massive brain injury.

The results for blast-induced head accelerations presented within this paper have been obtained using a triaxial head accelerometer cluster installed in the heads of both Hybrid II mannequins. Experiments were conducted with the mannequins not wearing any protective clothing at first, followed with the mannequins fully dressed in various protective ensembles. By comparing the resultant peak head accelerations measured at the same nominal test conditions, an attempt was made to assess the level of impact protection offered by different helmets and suits against blast induced head acceleration.

Table 2 lists the average values of blast induced head acceleration and the measured ranges as a function of nominal side-on overpressure.

nominal side-on overpressure [bar/psi]	**blast induced head acceleration average / range [g's]**
4.7 / 68	**57.3** / (44 - 83)
7.9 / 115	**110.3** / (78 - 168)
11.9 / 173	**182.7** / (157 - 229)

Table 2: Blast induced head acceleration, measured behind an EOD-8 ensemble frontally hit by a blast wave, as a function of nominal side-on overpressure

Figure 3 illustrates that protection of the mannequin with the EOD-8 ensemble changes the acceleration characteristics very significantly (lower trace). Peak values are reduced by as much as 85 % and are only reached in a more gradual fashion compared to the unprotected case (upper trace).

Earlier test series confirmed that the indicated level of protection can only be achieved if the helmet is worn in conjunction with a corresponding protective suit – the complex flow field establishing around the body of a person hit by a blast wave would lead to higher head accelerations if part of the blast were not deflected and absorbed by the suit, in particular by the extended protective collar, which assists in shielding the head and neck regions while maximizing the range of motion.

Further details concerning these measurements are outlined in [1]. Based on an injury model described in [4], the acceleration readings can be used to assess the injury risk. The data can then be summarized graphically in the form of Fig. 4 and the right side of Fig. 2b, which allows one to estimate the head injury probability as a function of blast side-on overpressure (both figures contain essentially the same information - however, the presentation in Fig. 2b is more suitable for a quick graphical injury assessment). As can be observed, from the cases studied, all peak head acceleration levels measured for unprotected mannequins indicate potentially fatal consequences, while all readings for the mannequin protected with the EOD-8 ensemble clearly show survivable outcomes, although the severity of injury escalates with increasing blast overpressure (related to an increase in explosive charge mass or a smaller stand-off distance). Higher readings, and thus lower protection performances, were obtained in tests with open-faced and rigidly mounted visors as well as in trials where the helmet rear was loaded with the blast wave [1] (see Fig. 4 and middle column of right side of Fig. 2b).The type of the shock absorbing system, e.g. between helmet and visor, and the orientation towards the blast center were thus shown to have a significant influence on the protective performance of an ensemble. From Fig. 2b it can be seen for instance that at a side-on overpressure of 5 bar (72.5 psi), a frontal loading would likely lead to a minor to moderate injury for a protected individual, while the same impact to the rear of the helmet can be expected to cause serious to severe injury.

For a protected mannequin, the impact to the ground (deceleration) proved to be generally more benign than the initial head acceleration caused by the blast. The test data indicate that the initial loading (acceleration) is the main concern and source of injury (as can be seen by comparing the left and the right columns in the right part of Fig. 2b). The violence of the blast impact became evident in the displacement of the mannequin as a result of the frontal load, which ranged from 0.5 to 5.5 m (1.6 ft to 18 ft) over the range of overpressures tested.

It must be emphasized that the use of a single parameter for injury assessment can only be considered as a starting point without implying that this is the only significant injury mechanism parameter worth measuring. There may well be others, which for a variety of reasons, could not be included in the present study. The results and injury predictions presented here are preliminary and are intended to represent an estimate of threat rather than a definitive measure of injury risk.

In order to minimize the possibility of serious and life-threatening injuries, it is apparent from the previously presented results that an individual must carefully consider the charge mass and stand-off distance applied. The helmet type and the orientation of the individual with respect to the explosive source are also important parameters [1].

V. CONCLUSION

The conducted full-scale tests highlight the performance and limitations that can be expected of EOD protective ensembles with respect to their attenuation capability for overpressure and blast induced head acceleration. A better appreciation of the threat can prove useful in enhancing the safety of UXO clearance operations and render safe procedures (RSPs).

It became evident that for the range of typical explosion threats associated with charges that create side-on overpressures of 3 to approximately 12 bar (42.5 - 174 psi), **the blast attenuating features of the EOD-8 ensemble drastically reduce the risk and the level of injury that would be incurred as a result of blast overpressure**, compared to the case of no protection. In the frontal chest region, **peak overpressure imparted by an incident blast wave is reduced by nominally 85 %** (range of 65% and 90%). In the full-scale tests, the samples and the mannequins were hit by a wave system including ground-reflected waves, which increased both loading severity and duration.

The EOD-8 helmet in combination with the suit (and collar interface) **reduces overpressure to the ear by more than 92 %** and **peak head acceleration for frontal loading by nominally 85 %**. For adequately protected individuals, deceleration, e.g. by impact on the ground, was shown to be a less serious source of injury than acceleration. Another direct implication of the current results is that rear exposure to the blast is undesirable, particularly at short stand-off distances, as current protection levels in the rear are inferior to those for the front facing suit and helmet. Although considerable protection is afforded by the EOD-8 ensemble for rear exposures, superior protection levels are provided for the front facing orientation (jacket, trousers, helmet) due to the increased risk probability. Consequently, RSPs should consider the orientation of the technician in order to maximize the protection afforded by a protective ensemble.

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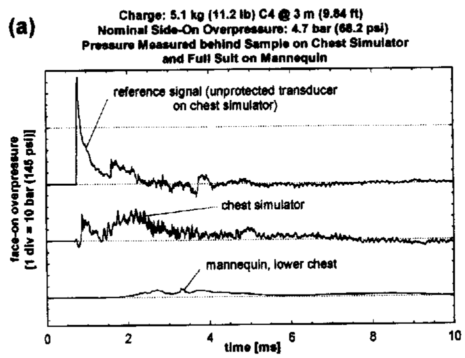

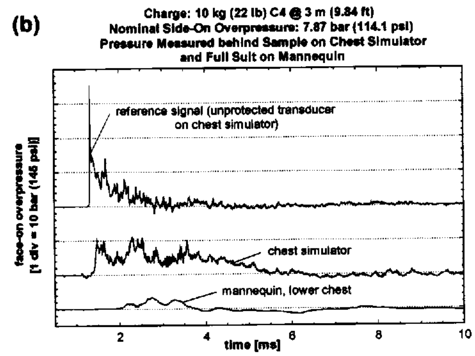

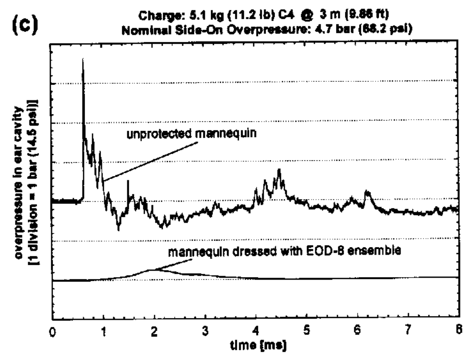

Figure 1: Overpressure reduction performance of the EOD-8 ensemble

a) chest lamination for side-on overpressure of 4.7 bar (68.2 psi)
b) chest lamination for side-on overpressure of 7.87 bar (114.1 psi)
c) helmet (overpressure in ear cavity) for side-on overpressure of 4.7 bar (68.2 psi)

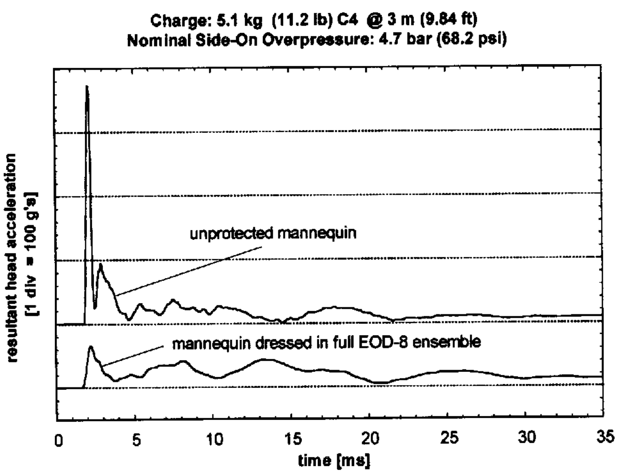

Figure 3:
Resultant head acceleration measured on a HYBRID II mannequin; unprotected mannequin (upper trace) and mannequin wearing the full EOD-8 ensemble (lower trace)

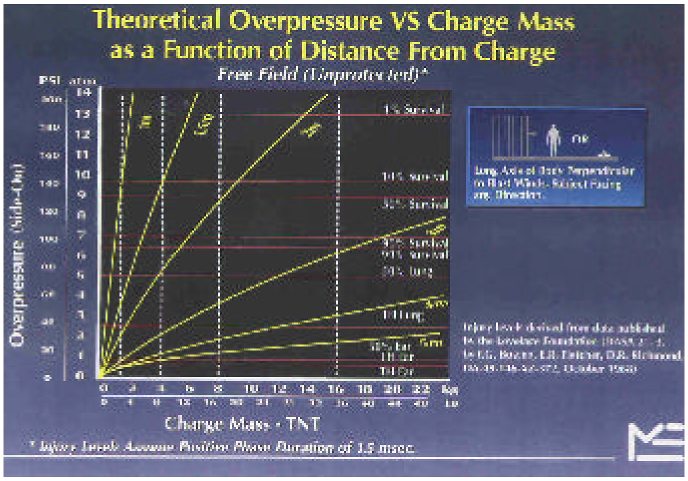

Figure 2a: Theoretical side-on overpressure versus charge mass as a function of distance from charge, indicating injury thresholds associated with blast induced overpressure for <u>unprotected individual</u>

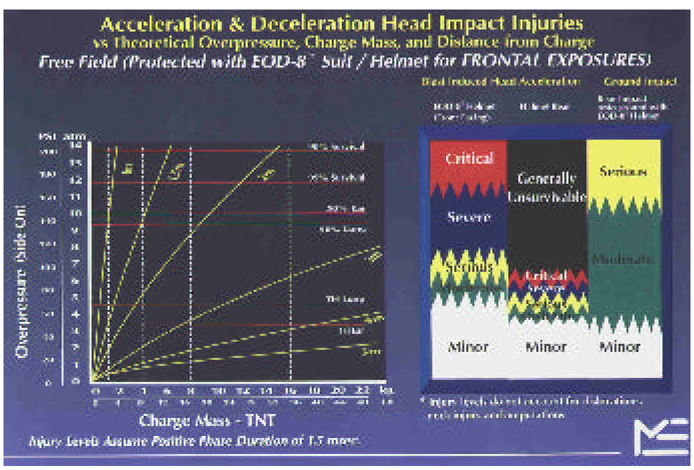

Figure 2b: Theoretical side-on overpressure versus charge mass as a function of distance from charge, indicating injury thresholds associated with blast induced overpressure for <u>individual wearing the EOD-8 ensemble</u> (left) and injury levels associated with blast induced head acceleration/deceleration (right)

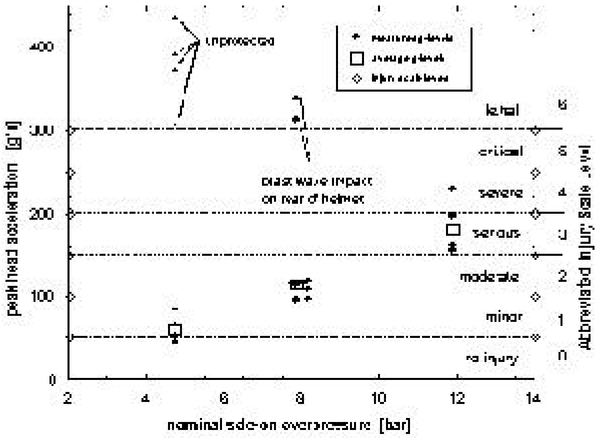

Figure 4:

Peak head acceleration, measured on HYBRID II mannequin, as a function of nominal side-on overpressure; horizontal lines indicate injury levels

Left: Photo 1 Test setup with both chest simulators and two HYBRID II mannequins wearing the EOD-8 ensemble shortly after the instant of charge explosion (5.1 kg / 11.2 lb C4 @ 3 m / 9.84 ft); photos from two different trials

Bottom left: Photo 2a Initial setup of large-scale tests with (from left to right) chest simulator, lollipop pressure transducer, charge (10 kg / 22 lb) and HYBRID II mannequin dressed in EOD-8 ensemble

Bottom right: Photo 2b Instrumentation of mannequin HYBRID II